# Solar Energetic Particles (SEPs) and Space Weather

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# Solar Energetic Particles

- The Sun accelerates particles to near-relativistic speeds
  - Particles = electrons, protons, ions
  - Near-relativistic speed = near the speed of light ($c = 300{,}000\ \mathrm{km/s}$)
  - Accelerated particle energies up to ~GeV ions.
  - Higher energy than ambient solar wind
- Most of the acceleration happens close to the Sun (less than 10 Rs)
- Particles can reach Earth's orbital distance (1 AU) in tens of minutes to hours

# Particle Energy units

- The electronvolt (eV) is a unit of energy
- $1\ \mathrm{eV} = 1.6 \times 10^{-19}$ Joules
- $1\ \mathrm{MeV} = 10^{6}\ \mathrm{eV}$, $1\ \mathrm{GeV} = 10^{9}\ \mathrm{eV}$

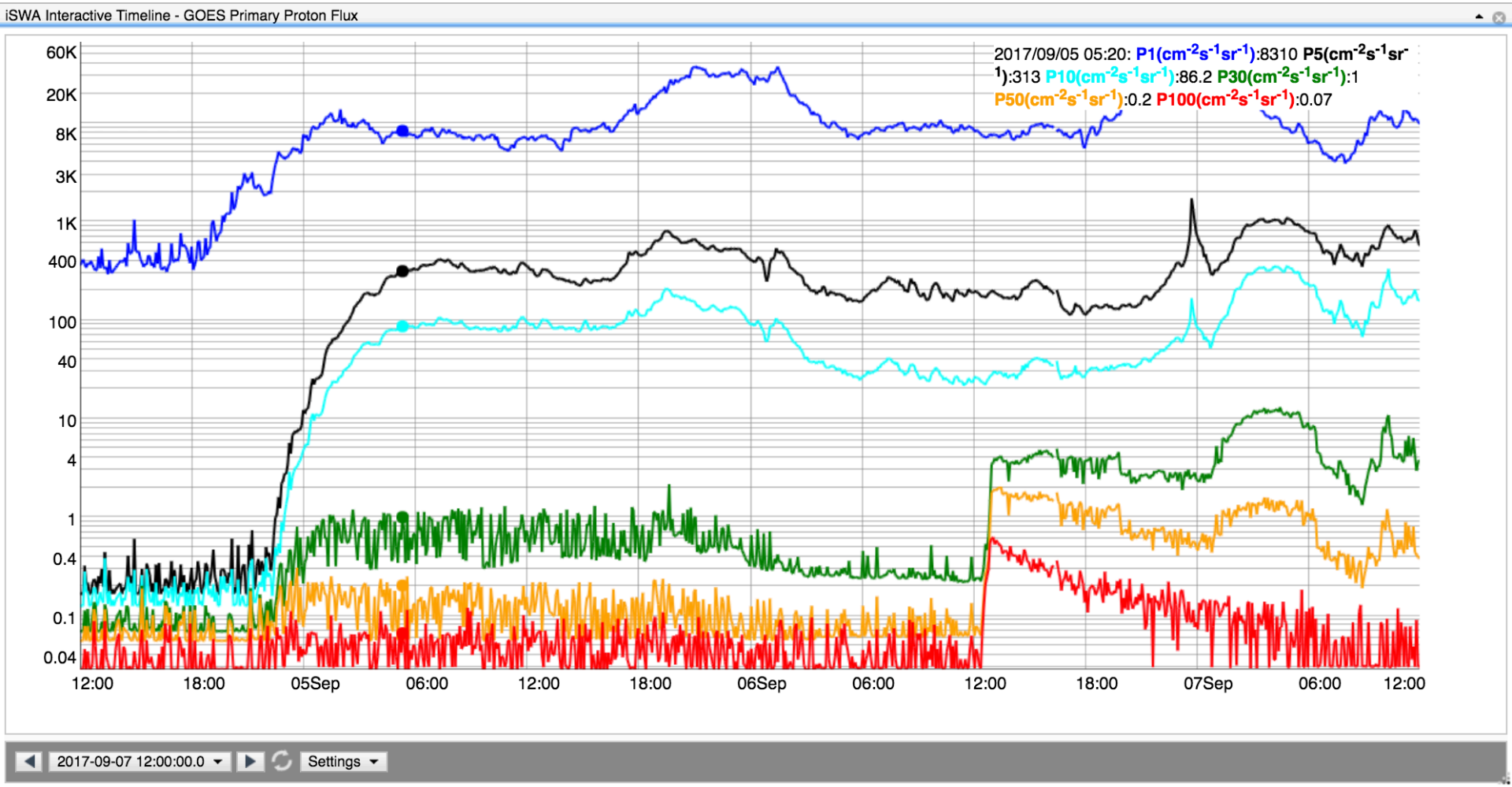
Examples:

- A 1 MeV proton is moving at 0.05c
- A 10 MeV proton is moving at 0.14c
- A 100 MeV proton is moving at 0.43c
- A 1 GeV proton is moving at 0.88c

# Flux units

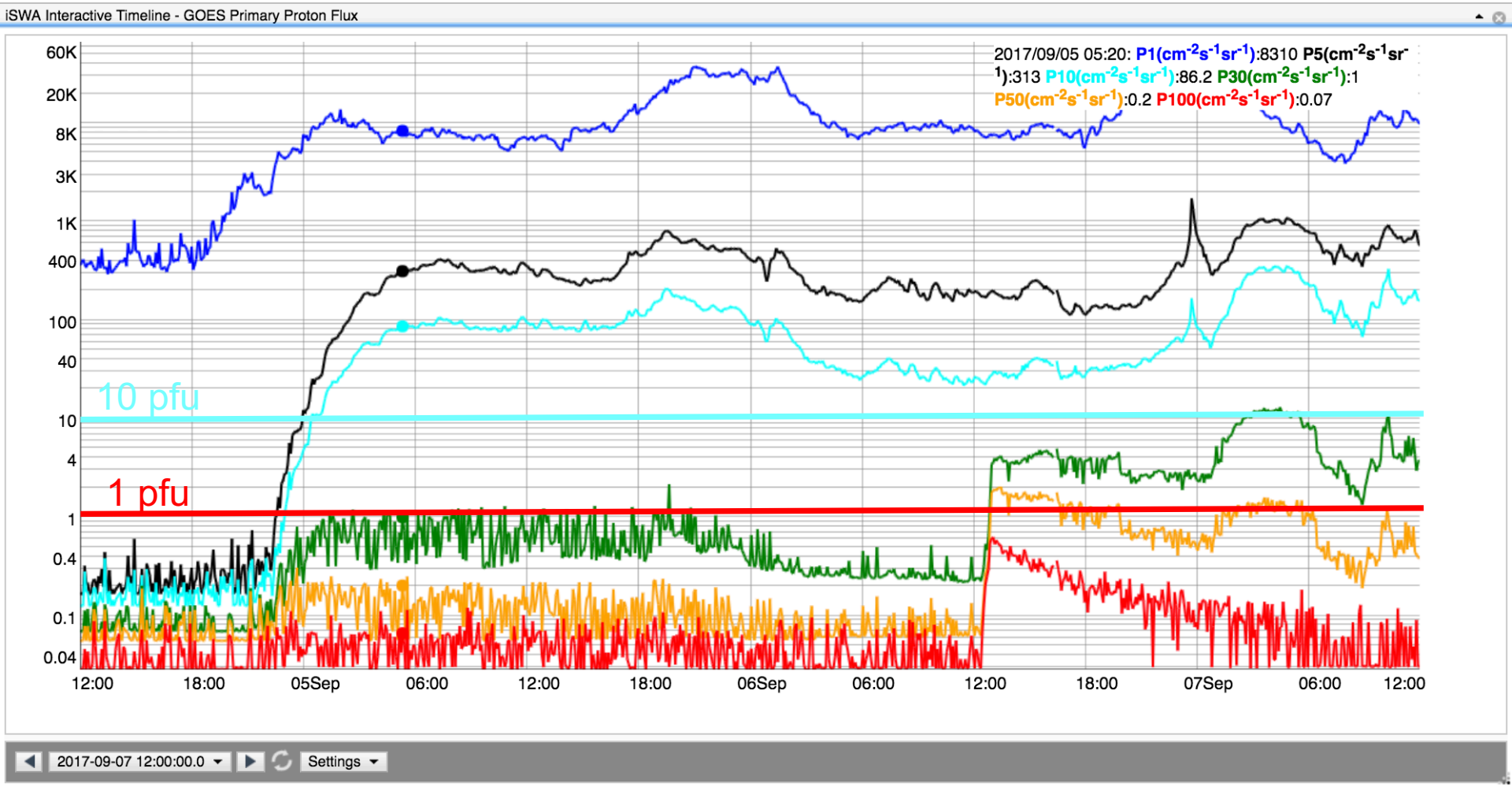
- pfu = particle flux unit
- 1 pfu = particles/(cm$^2$ sec sr)
- sr = steradian or square radian; unit of solid angle

# SEPs observed by GOES: proton flux vs time




integral proton flux (pfu) in 6 energy channels:
>1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV, >100 MeV

# SEPs observed by GOES: proton flux vs time

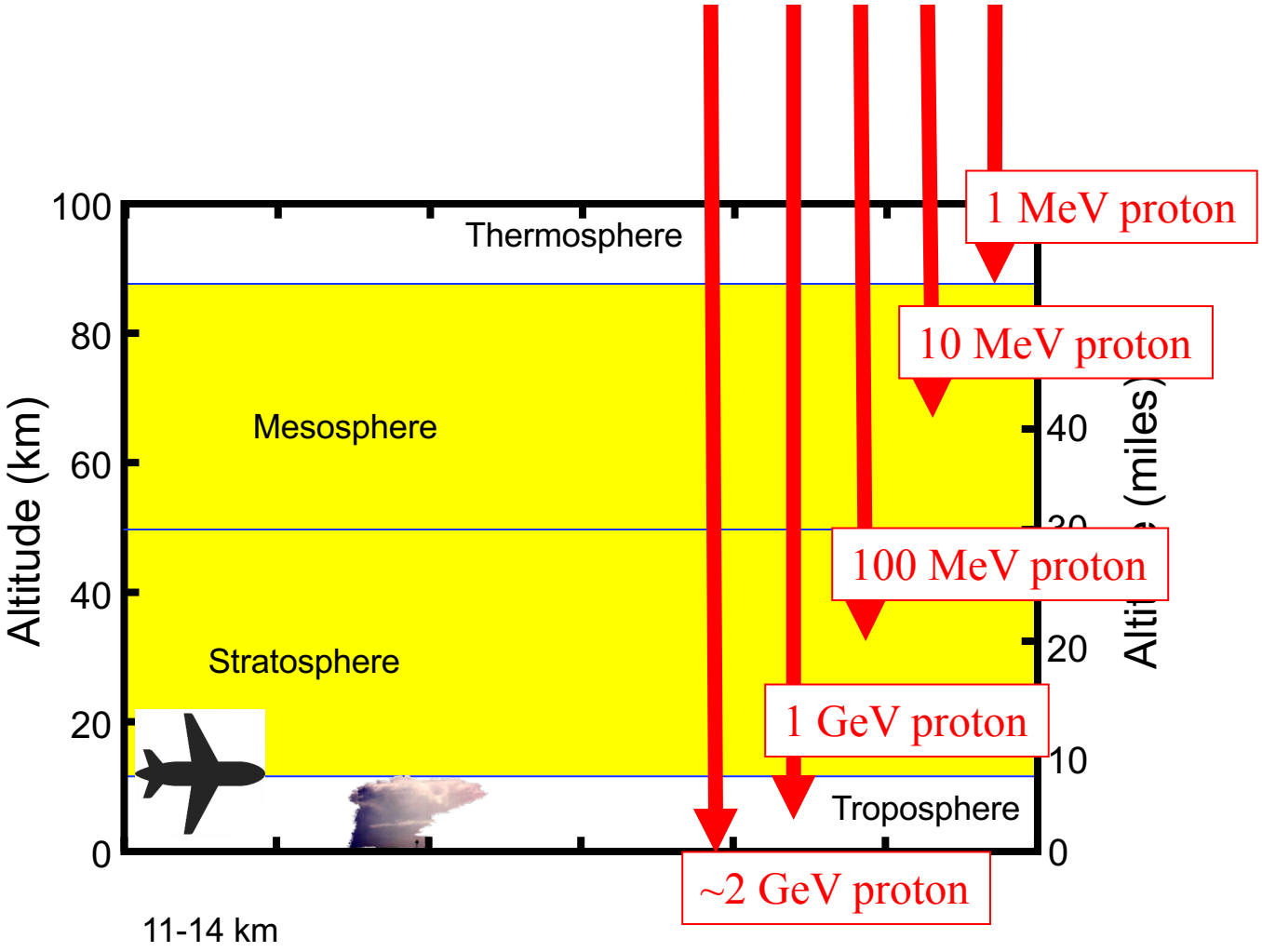



integral proton flux (pfu) in 6 energy channels:
>1 MeV, >5 MeV, **>10 MeV**, >30 MeV, >50 MeV, **>100 MeV**

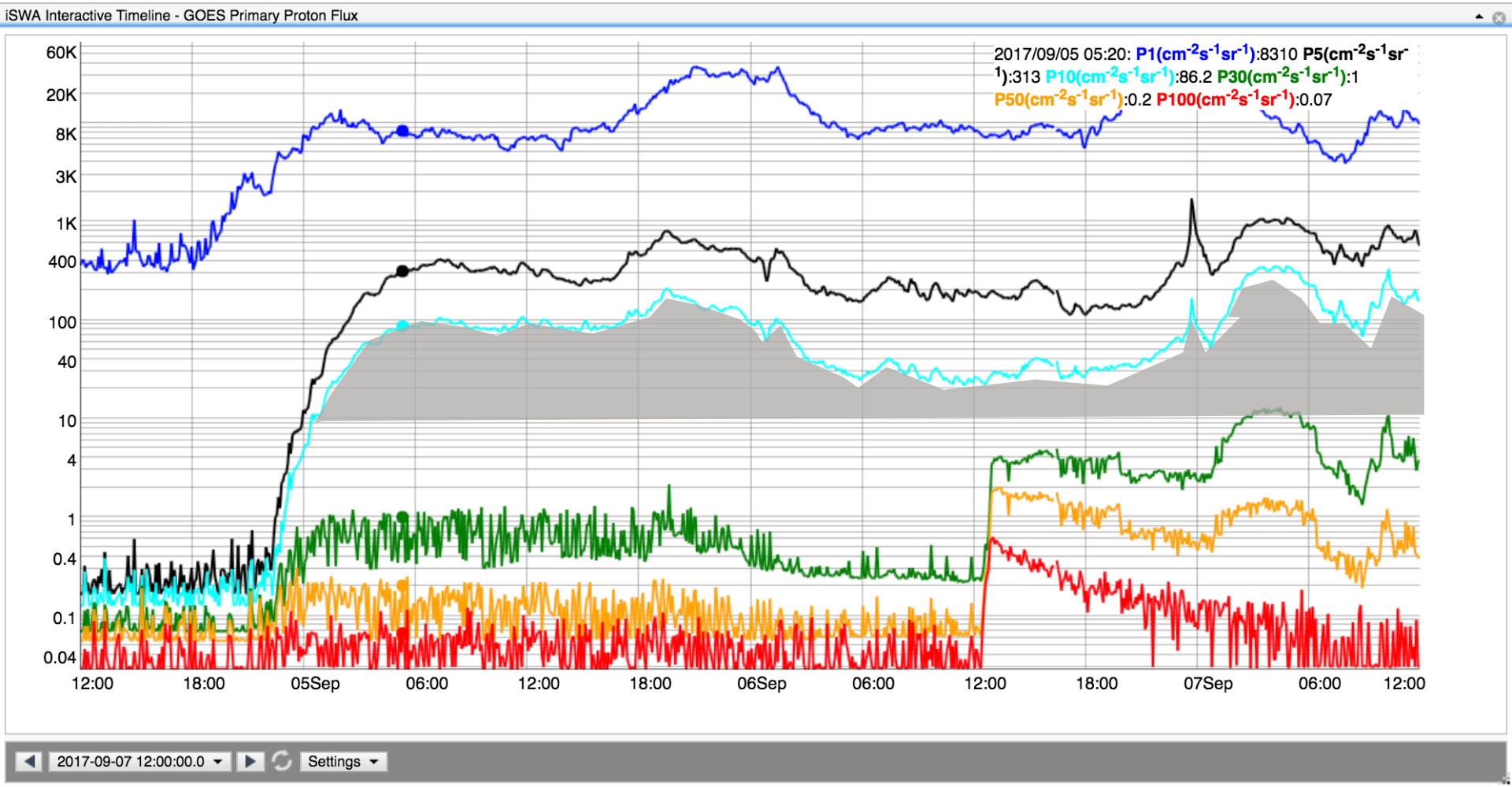
**Notification threshold: 10pfu** **1 pfu**

## NOAA Space Weather Scale for Solar Radiation Storms

| Category | | Effect | Physical measure | Average Frequency (1 cycle = 11 years) |
|---|---|---|---|---|
| Scale | Descriptor | Duration of event will influence severity of effects | | |
| **Solar Radiation Storms** | | | Flux level of >= 10 MeV particles (ions)* | Number of events when flux level was met (number of storm days**) |
| S 5 | Extreme | **Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***<br>**Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.<br>**Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult. | $10^5$ | Fewer than 1 per cycle |
| S 4 | Severe | **Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***<br>**Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.<br>**Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely. | $10^4$ | 3 per cycle |
| S 3 | Strong | **Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***<br>**Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.<br>**Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely. | $10^3$ | 10 per cycle |
| S 2 | Moderate | **Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***<br>**Satellite operations:** infrequent single-event upsets possible.<br>**Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected. | $10^2$ | 25 per cycle |
| S 1 | Minor | **Biological:** none.<br>**Satellite operations:** none.<br>**Other systems:** minor impacts on HF radio in the polar regions. | 10 | 50 per cycle |

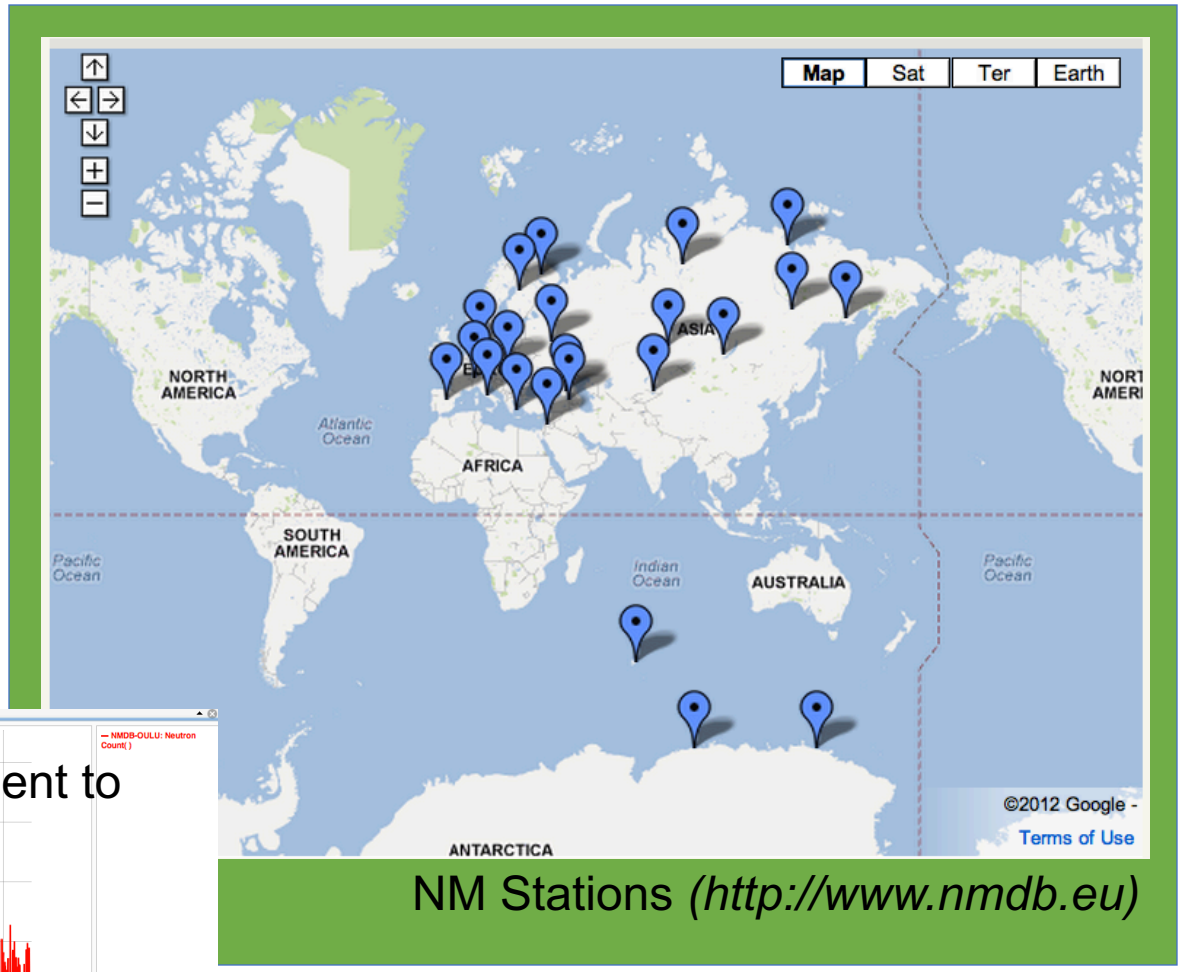

100
80
60
40
20
0
Altitude (km)
40
20
10
0
Thermosphere
Mesosphere
Stratosphere
Troposphere
11-14 km
1 MeV proton
10 MeV proton
100 MeV proton
1 GeV proton
~2 GeV proton

# Fluence=integrated proton flux over time, used to determine dose

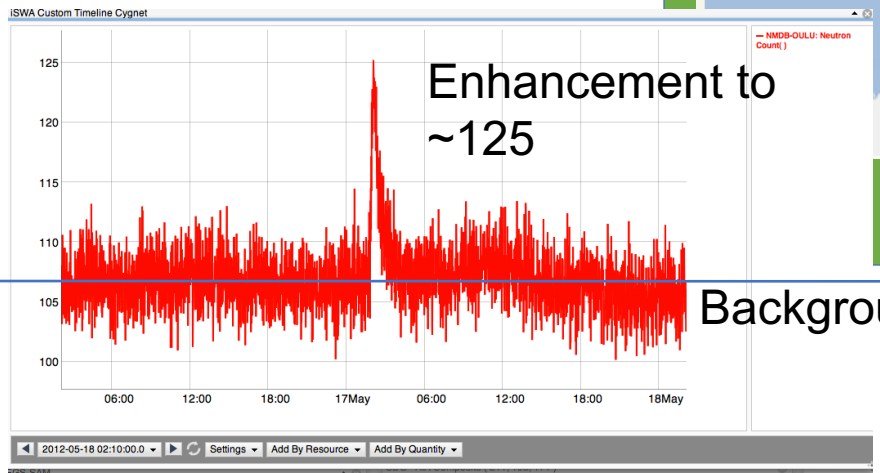


# Ground Level Enhancements

- GLEs = subset of SEP events
- high energy protons (>500 MeV/nuc)
- Reach Earth's surface.
- Collisions in the atmosphere generate secondary particles that are measured at neutron monitor stations on the ground.




NM Stations *(http://www.nmdb.eu)*

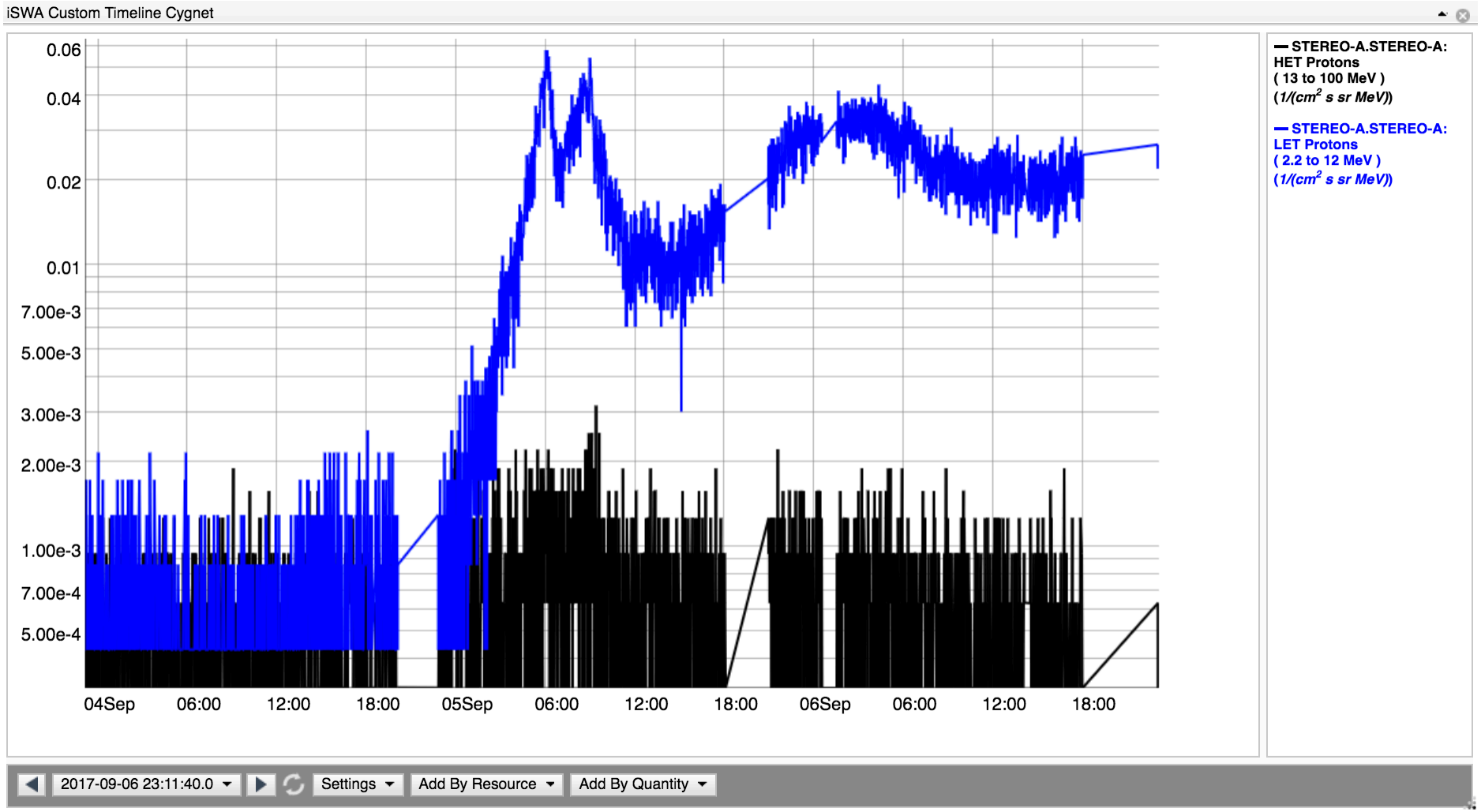



Enhancement to ~125

Background ~105

Neutron Monitoring Station in Oulu, Finland

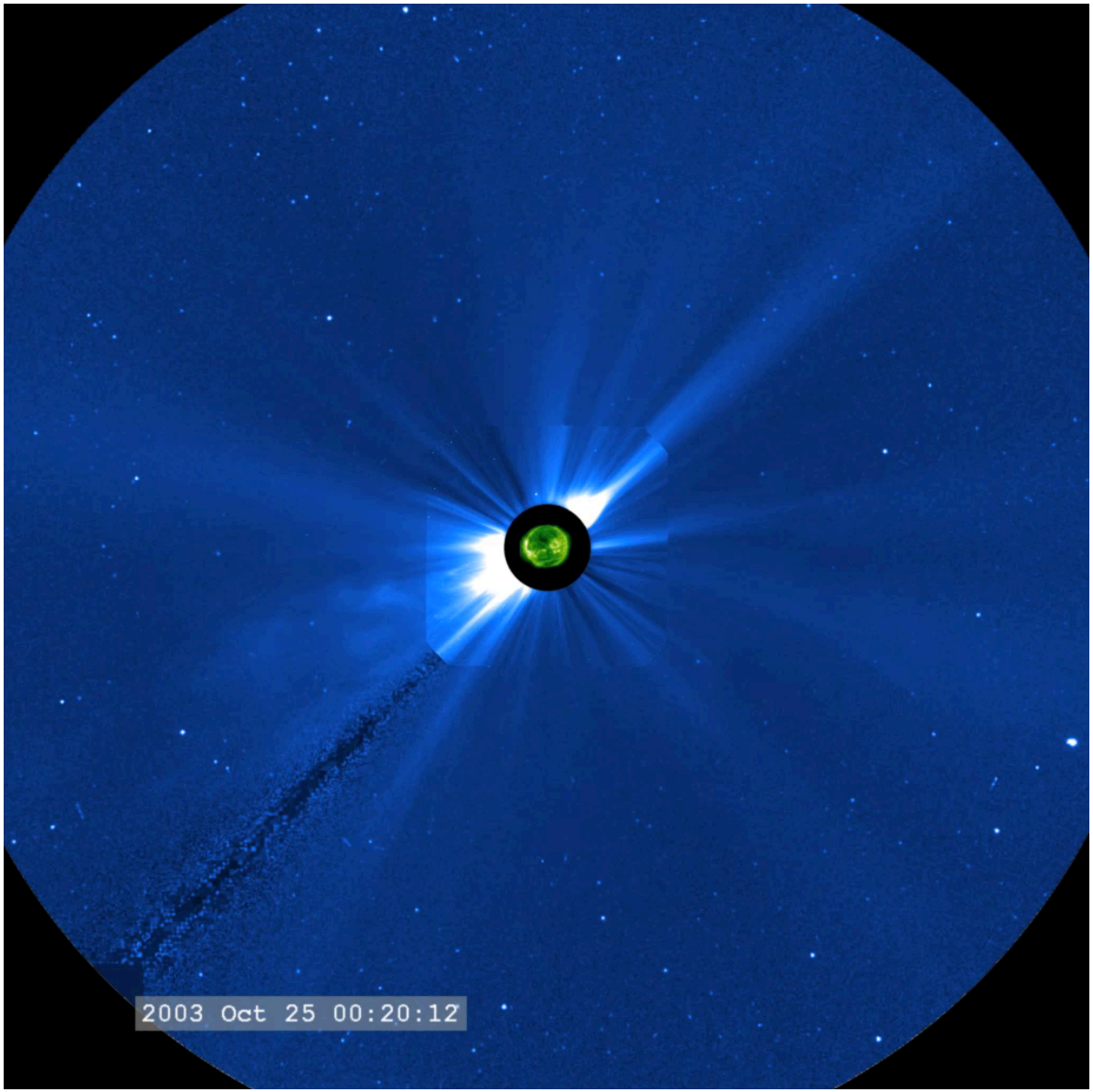
# SEPs observed by STEREO A: proton flux vs time




differential proton flux (pfu/MeV) in 4 energy channels (two shown): 0.14-0.62 MeV, 0.62-2.22 MeV, **2.2-12 MeV, 13-100 MeV**

Notification threshold: 0.1 pfu/MeV

# Solar Energetic Particles Hitting a Coronagraph



# Navigate to this webpage:

## http://qdle.net/24981545

# What is a space weather effect from SEPs?

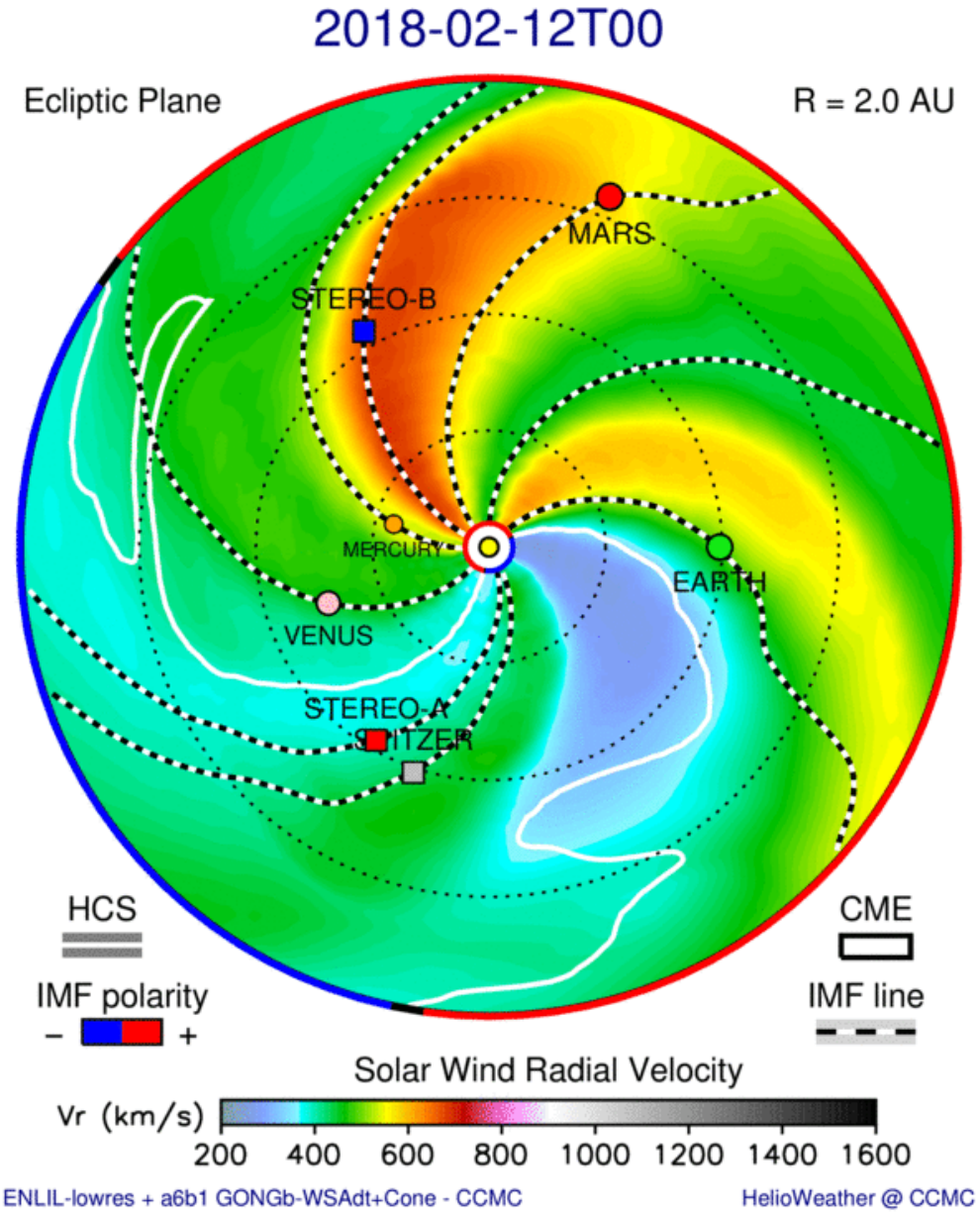
a) Increased radiation risk for astronauts on the ISS
b) Increased radiation risk for future human exploration missions throughout the solar system
c) Increased radiation risk for airline passengers and crew
d) Satellite solar panel degradation
e) Satellite processor and memory errors
f) All of the above

**Answer the quiz here:**

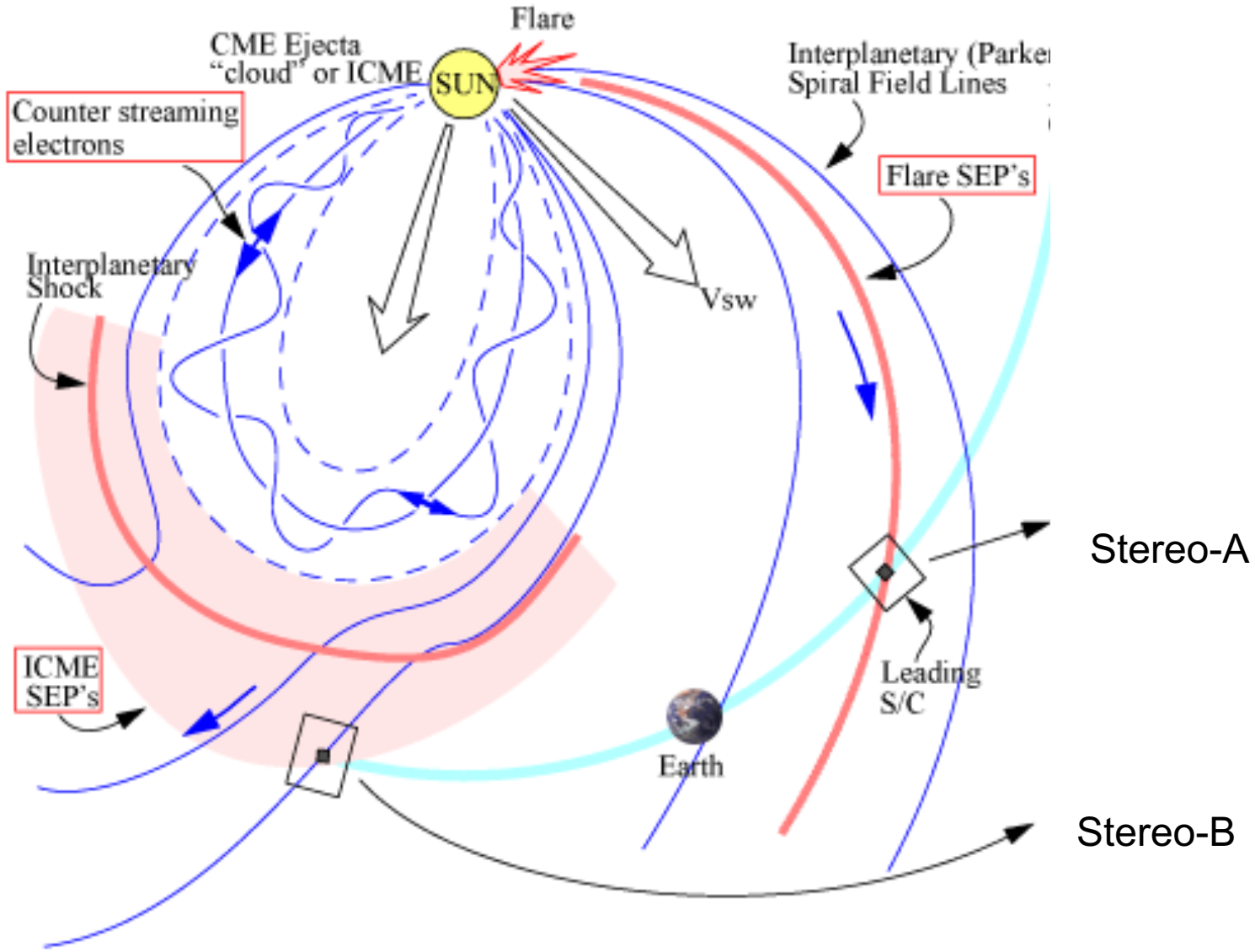
**http://qdle.net/24981545**

- The solar wind forms a spiral.
- The Sun's magnetic field also follows this spiral.
- Charged particles travel along these field lines (circling them)

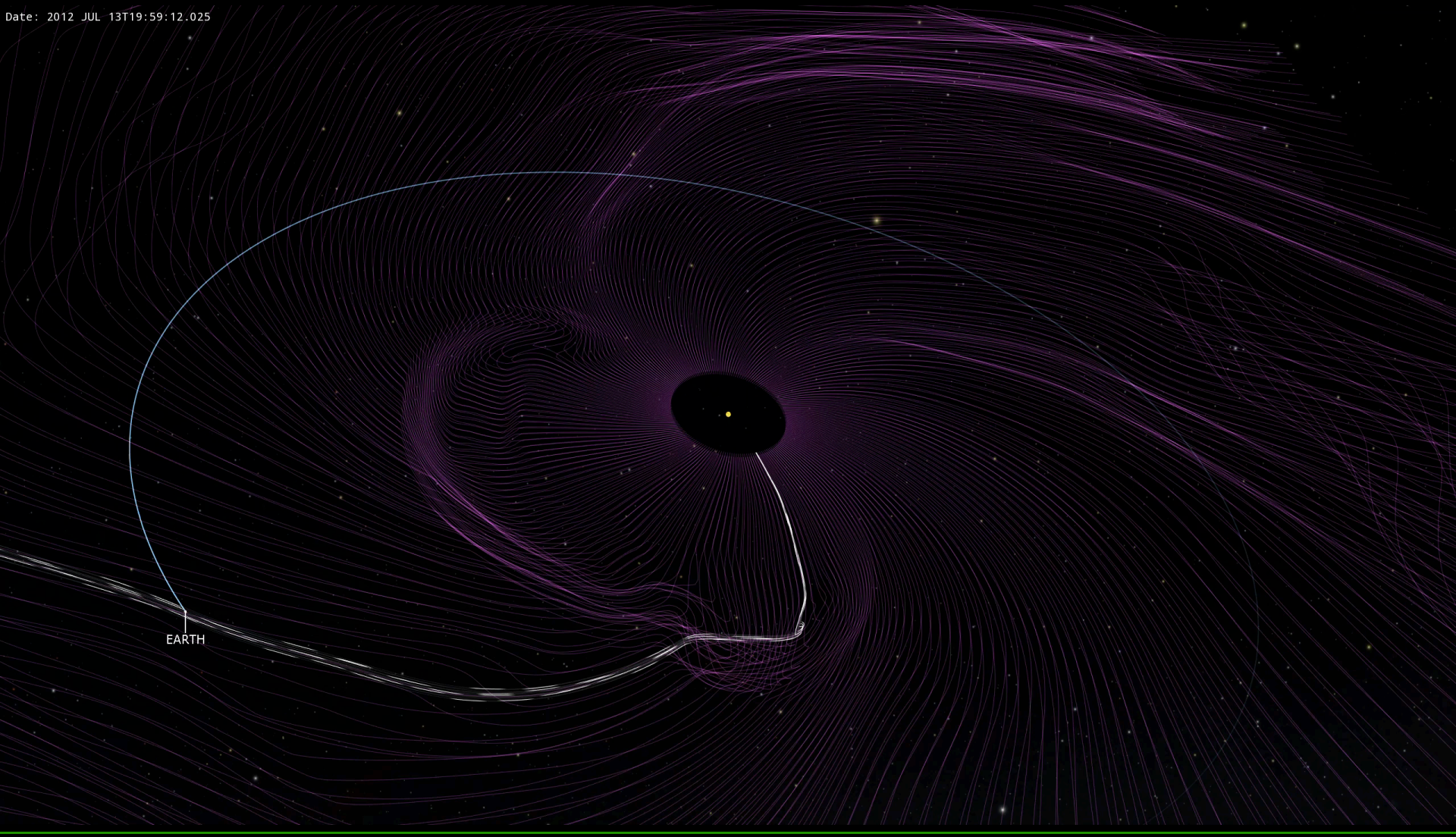
$$\mathbf{F} = \mathrm{q}\ \mathbf{v} \times \mathbf{B}$$




*WSA-ENLIL model: Solar wind velocity contour plot in the ecliptic plane*




Slide from J. Luhmann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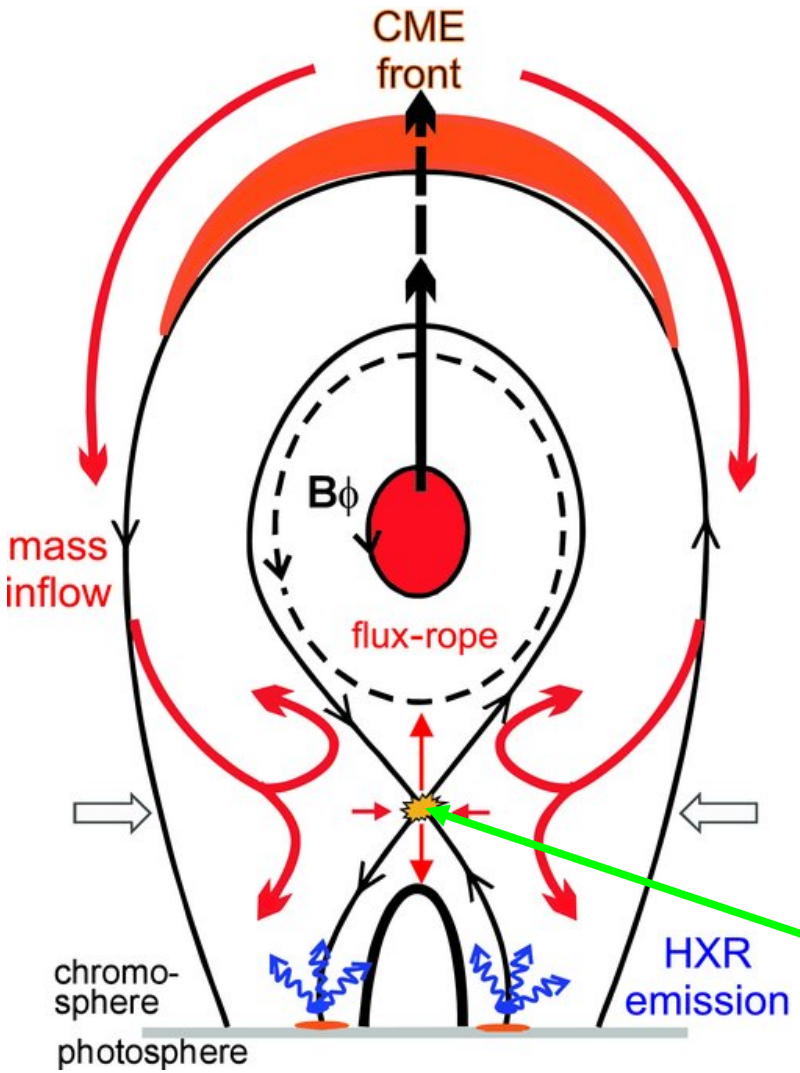
EARTH

Acceleration Mechanisms are still the topic of heated debate

- Solar Flares (e.g., reconnection; wave-particle interactions)
- CME-driven shocks
- A combination of processes, e.g., initial flare acceleration followed by shock acceleration?
- Flanks of CME-driven shock accelerate seed population from *previous flares*.

Slide from I. G. Richardson




*Adapted from Temmer et al.*, 2010

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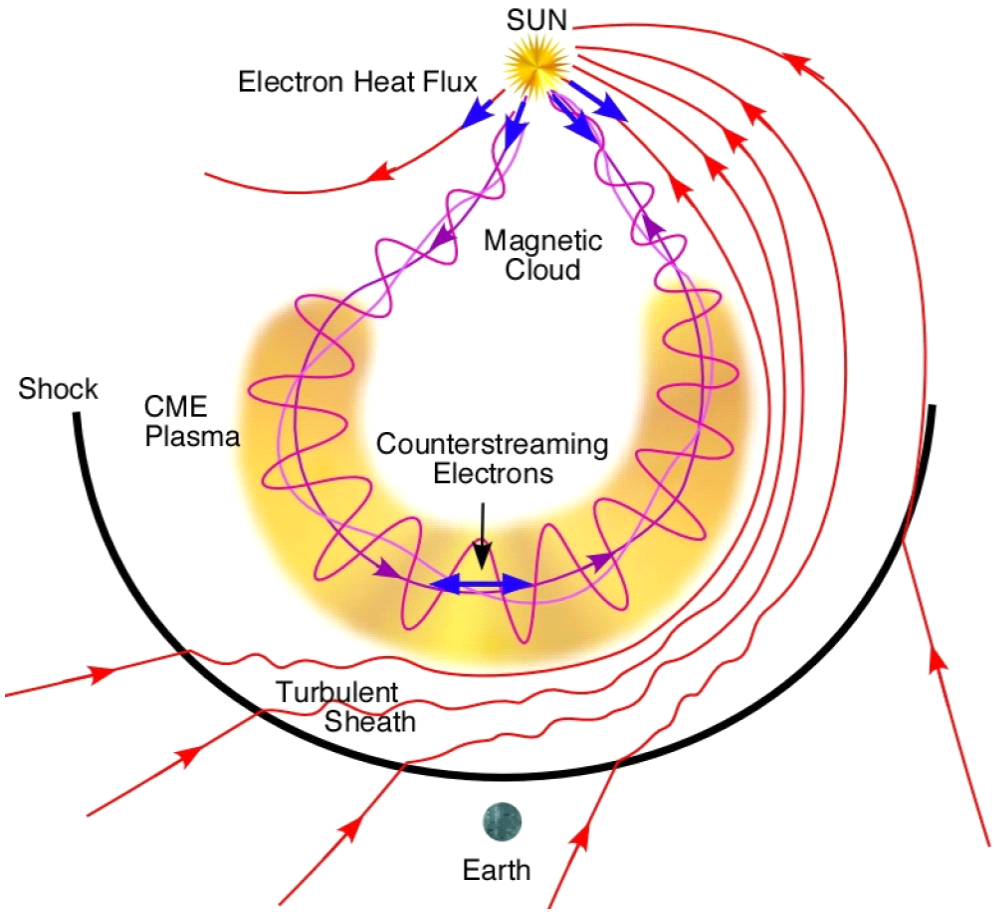
Particle acceleration by reconnection at neutral line below CME

Slide from I. G. Richardson

# Shocks Associated With Interplanetary Coronal Mass Ejection (ICMEs) Can Accelerate Particles




*Zurbuchen and Richardson*, 2006

Shock is formed ahead of fast ICMEs

Shock may accelerate particles as it moves out through the solar wind

Observer magnetic connectivity matters

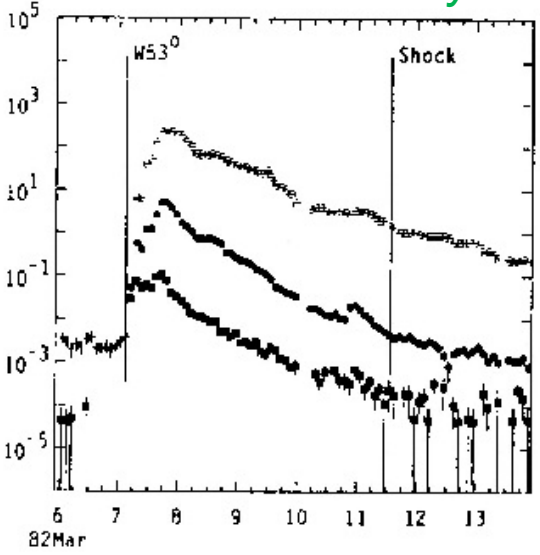
Slide from I. G. Richardson

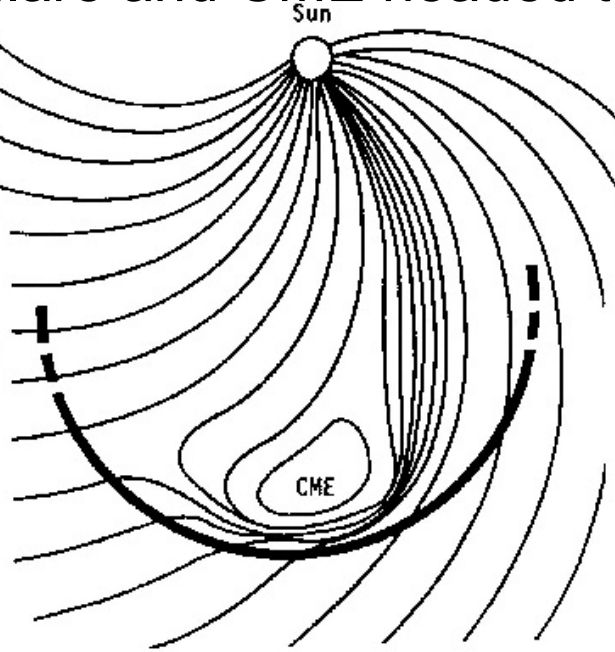
# Longitudinal difference in proton flux profiles

Central flare and CME headed towards Earth

Eastern observer

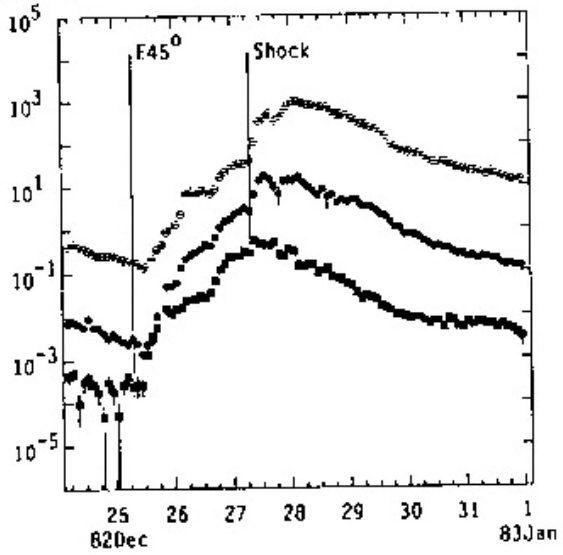
*well-connected early*

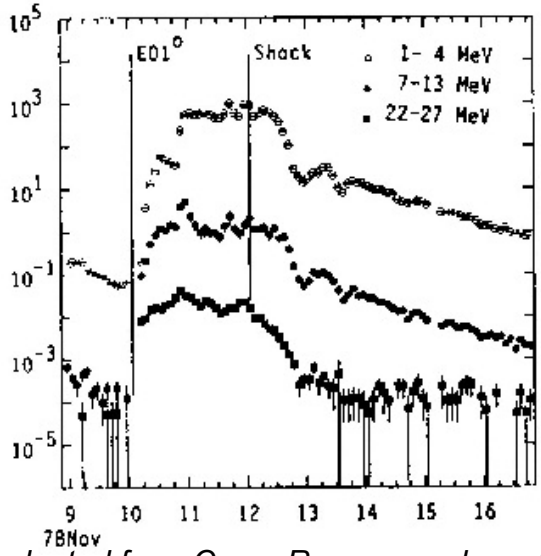



Western observer

*well-connected at observer*



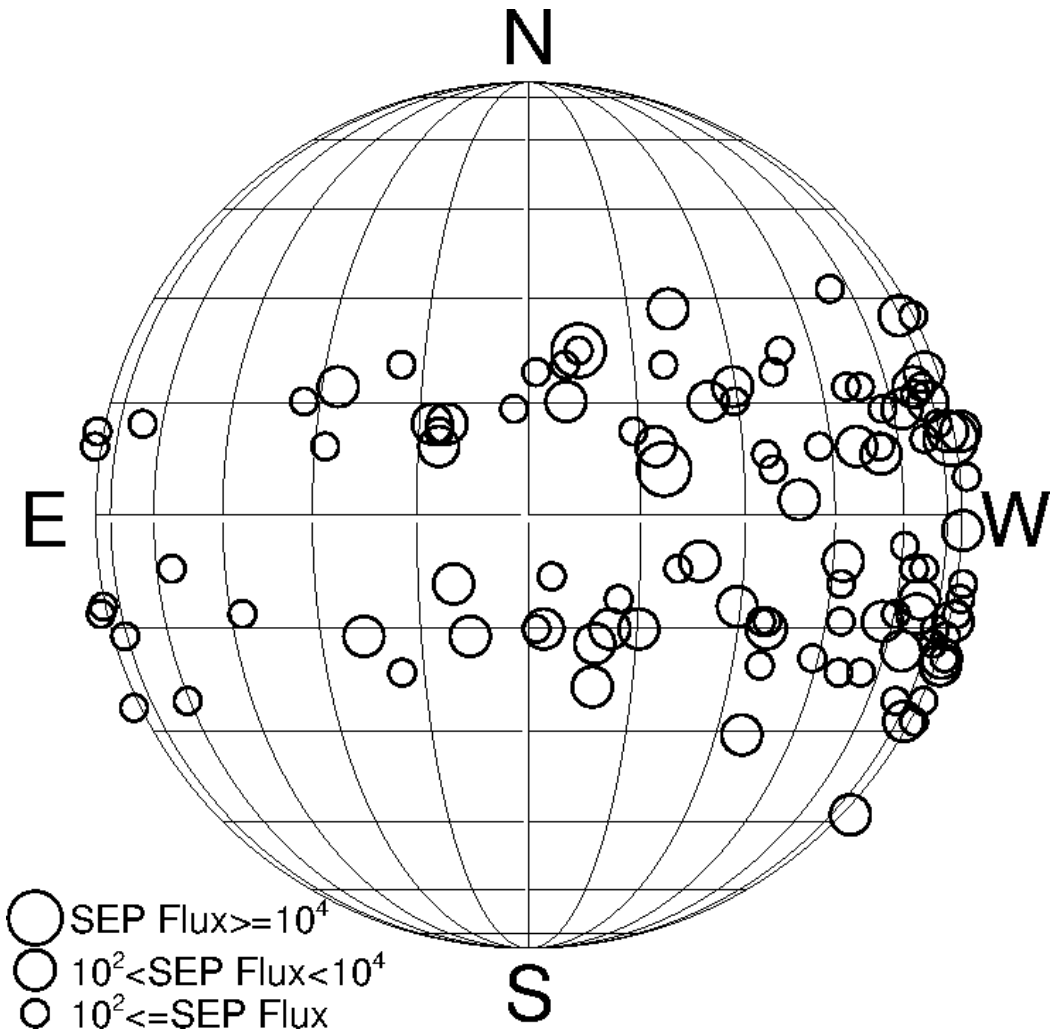




Earth observer

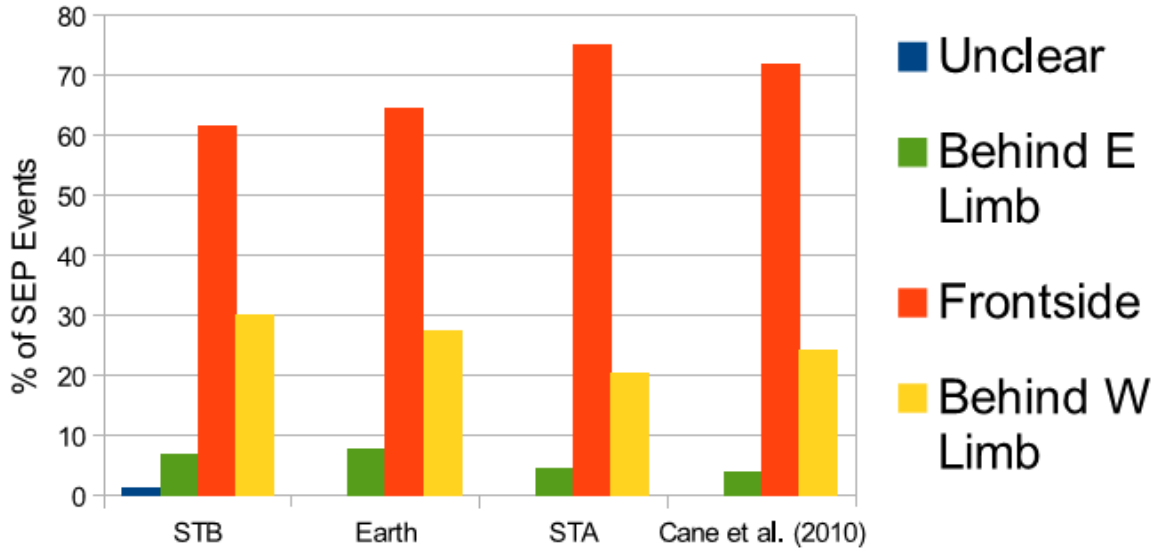
*well-connected midway*

*(from Reames, Space Science Rev., 1999, adapted from Cane, Reames and von Rosenvinge, 1988)*

# Distribution of front-side SEP source locations



# How many ~25 MeV Proton Events Originate Behind the Limb of the Sun?




Around 25% of events originate behind the west limb and ~5% behind the east limb. Asymmetry reflects connection via the spiral interplanetary magnetic field.

Similar results for each spacecraft/location

Slide from I. G. Richardson

# 25 MeV Proton Event Statistics (*Richardson et al.,* 2014)

~99% are associated with cataloged CMEs

52% are associated with “full halo” CMEs in the CDAW LASCO catalog

Percentage associated with X-ray flares:

| | |
|---|---|
| B-class | 7% |
| C-class | 37% |
| M-class | 40% |
| X-class | 16% |

WIND/WAVES/SWAVES Radio observations

Type II 53%; IP type II (< 1 MHz) 33%

Type III 92%

Slide from I. G. Richardson

# What is the solar source location for most SEPs with respect to an Earth observer?

a) From the backside of the Sun
b) From the western hemisphere and behind the western limb
c) From the eastern hemisphere
d) Behind the east limb

**Answer the quiz here:**
**http://qdle.net/24981545**

# Why is the source location for most SEPs observed at Earth in the west?

a) There are more flares from the west limb
b) The solar cycle
c) There are more CMEs from the west limb
d) Favorable magnetic connectivity

**Answer the quiz here:**
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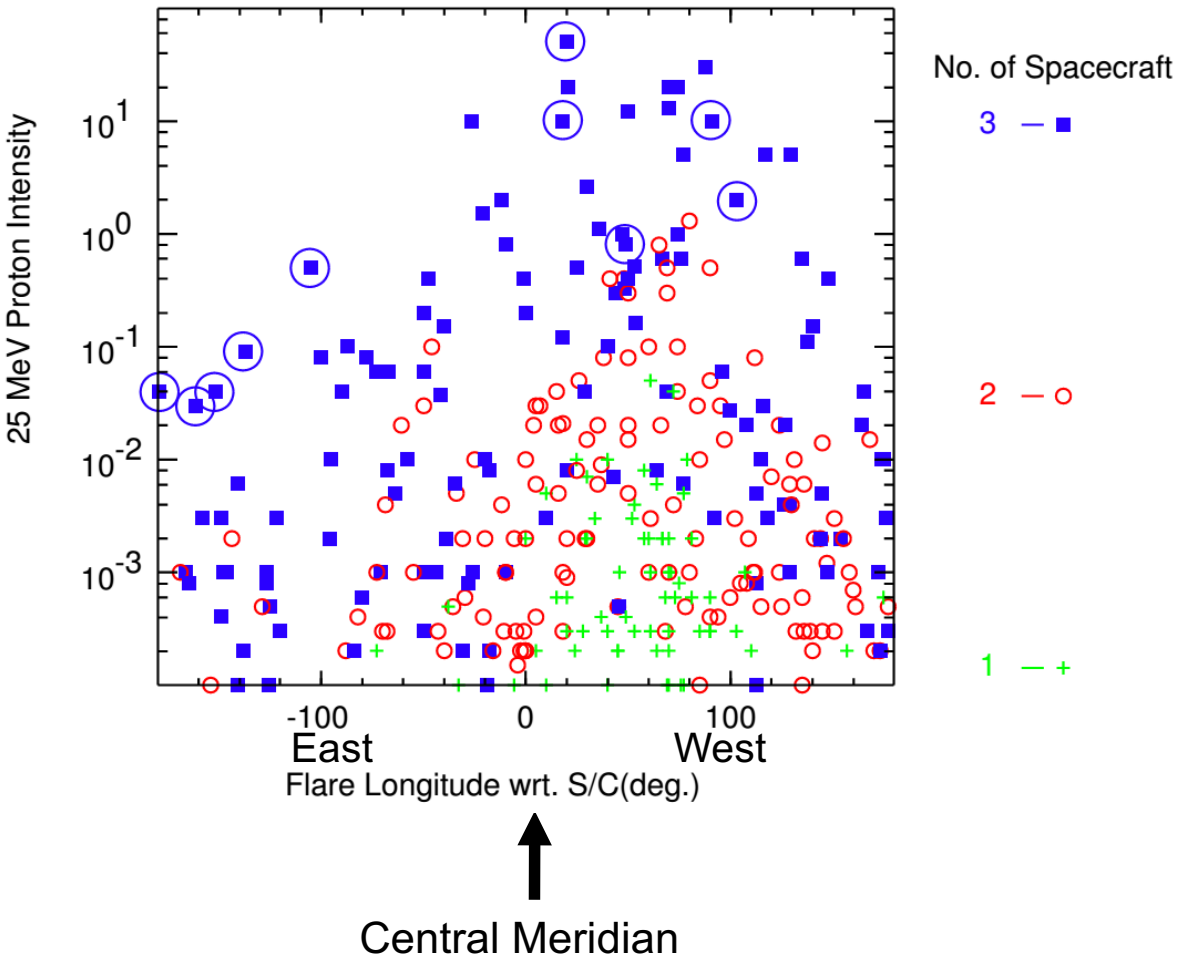
# Intensity of ~25 MeV Proton Events Plotted Against the Longitude of the Solar Event Relative to the Observing Spacecraft

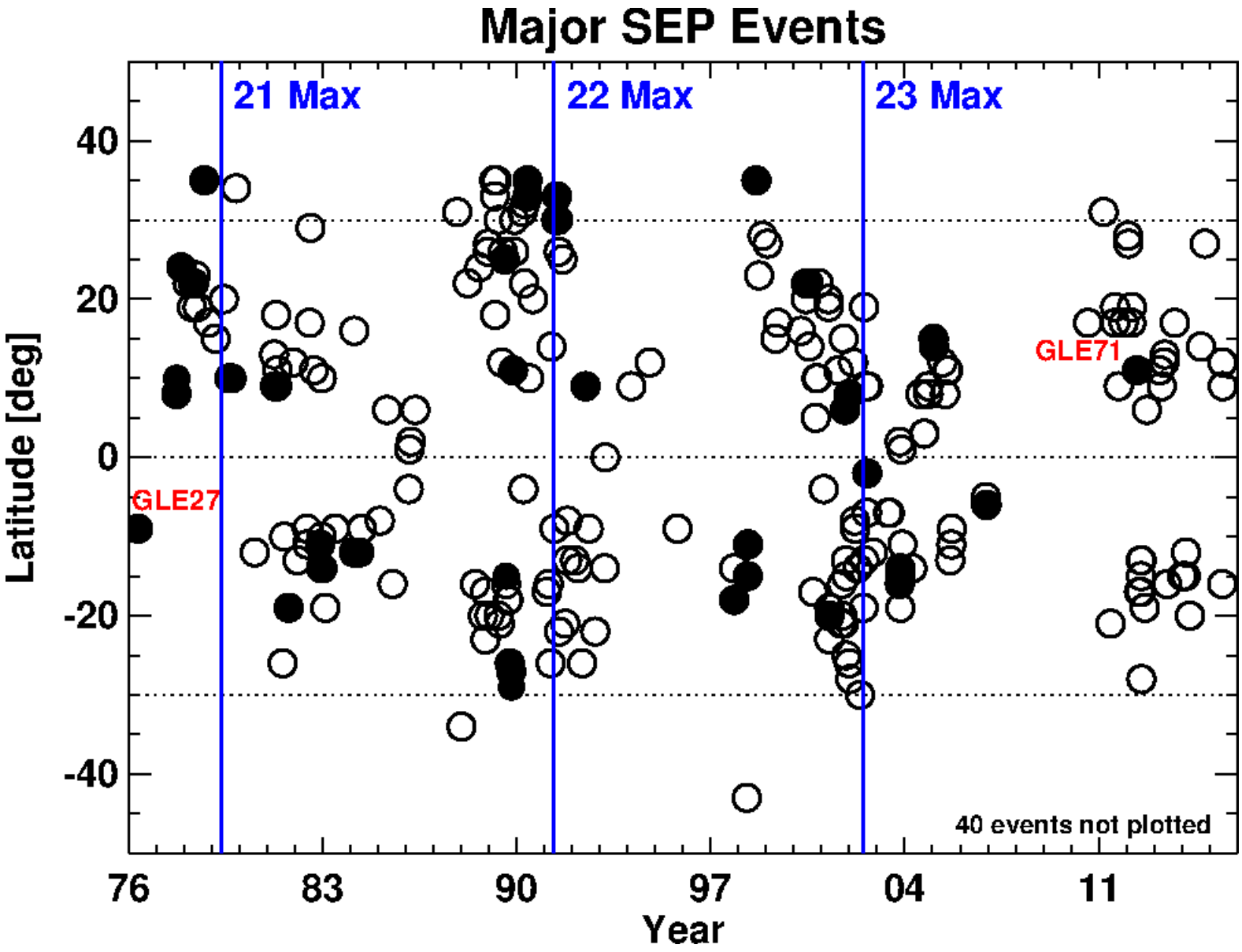



25 MeV Protons can be detected from anywhere on the Sun!

The intrinsic event intensity and spacecraft magnetic connection (~Parker spiral) are major influences on the observability of SEP events.

*Richardson et al.*, 2014

Slide from I. G. Richardson



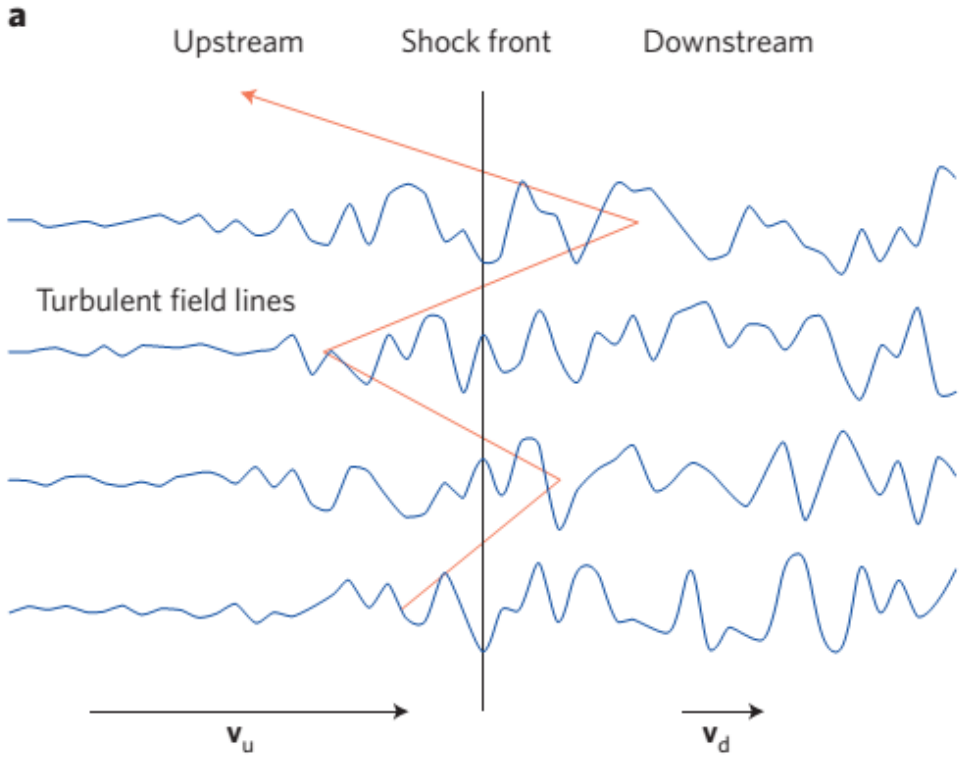

Slide from N. Gopalswamy

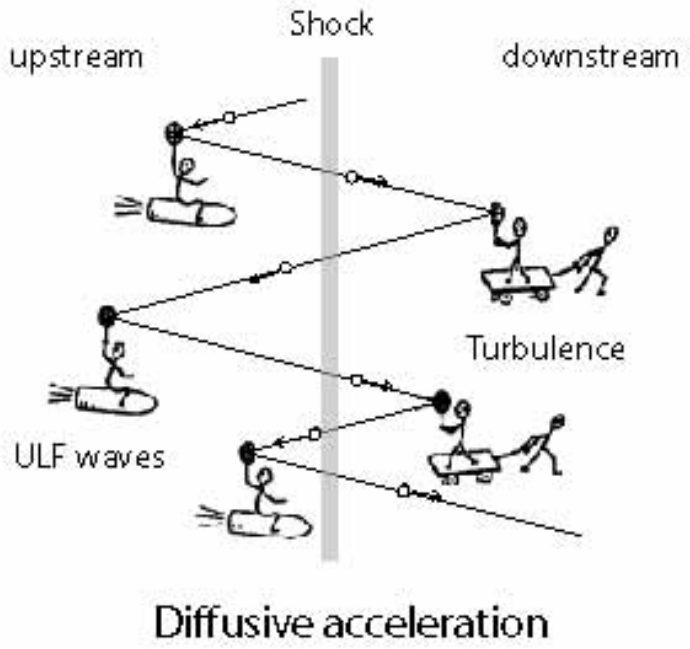
# Why are there more SEPs near solar maximum?

a) Better connectivity
b) More flares and CMEs
c) More variable solar wind speed
d) Solar magnetic field strength

**Answer the quiz here:**
**http://qdle.net/24981545**

# Particle Acceleration by Bouncing Between Converging Scattering Centers Upstream and Downstream of a Quasi-Parallel Shock (Diffusive Shock Acceleration)




*M. Scholer*

Quasi parallel = Upstream magnetic field ~parallel to shock normal.

Particle injection "problem" – particles must be able to propagate upstream of the shock ($V_{sw}$ ~ 1 keV >> thermal energy) )

Slide from I. G. Richardson

# Particle Acceleration at a Quasi-Perpendicular Shock – Shock Drift Acceleration

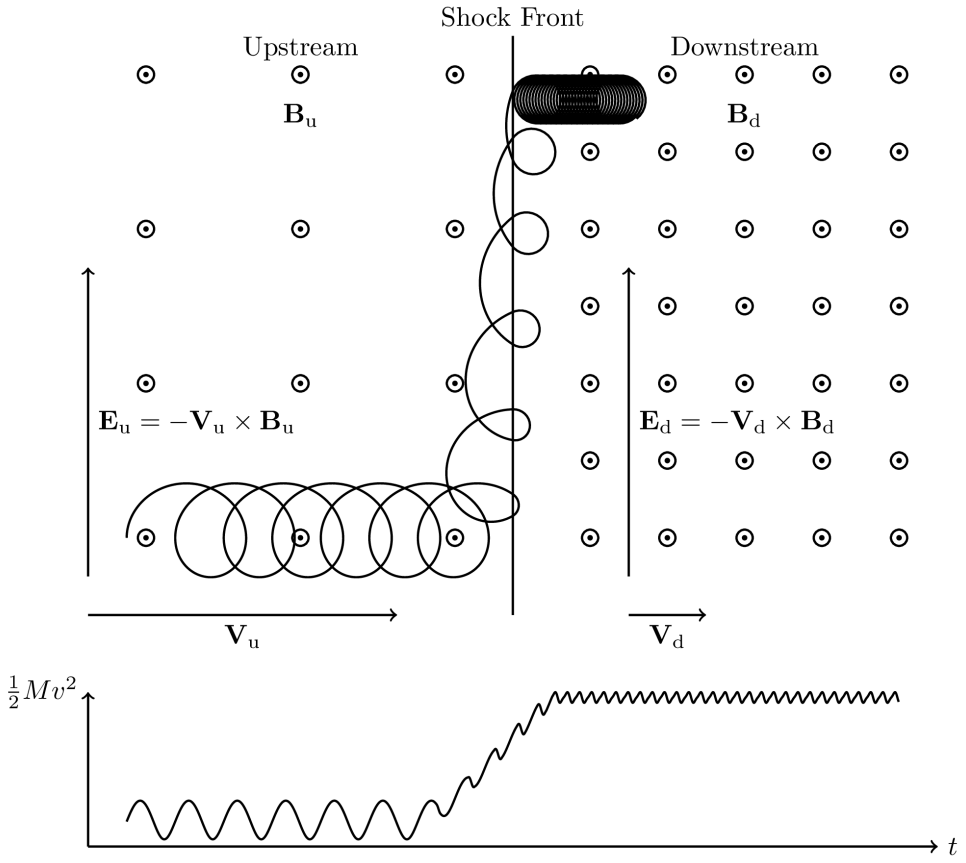



Figure by *M. Pulupa* after *Armstrong et al.,* 1985

Quasi perpendicular shock = Upstream magnetic field ~perpendicular to shock normal.

Process increases the particle velocity component perpendicular to B

Slide from I. G. Richardson

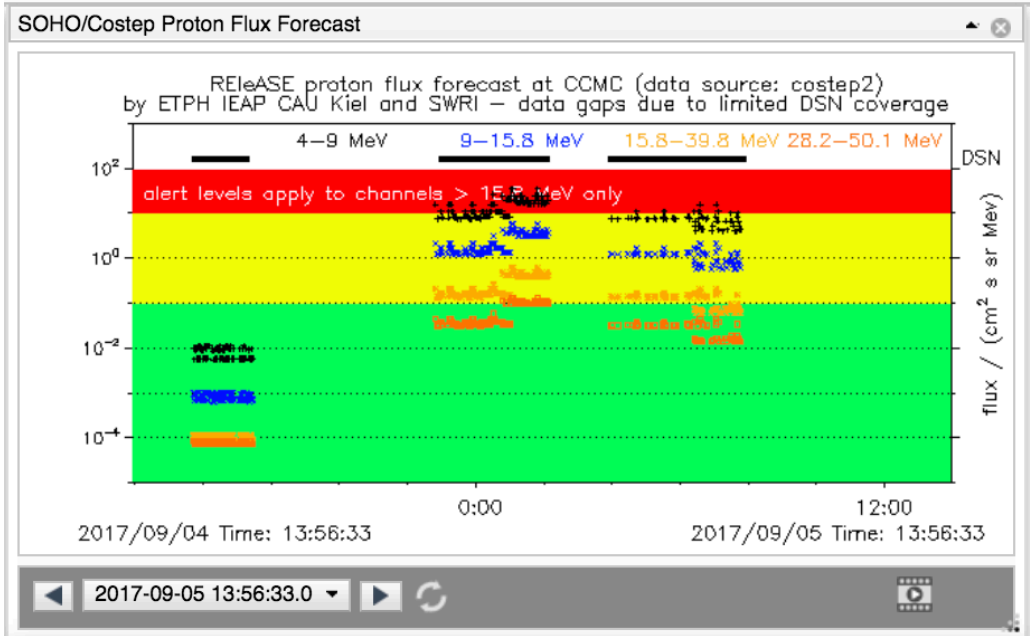
# SEP Prediction at CCMC

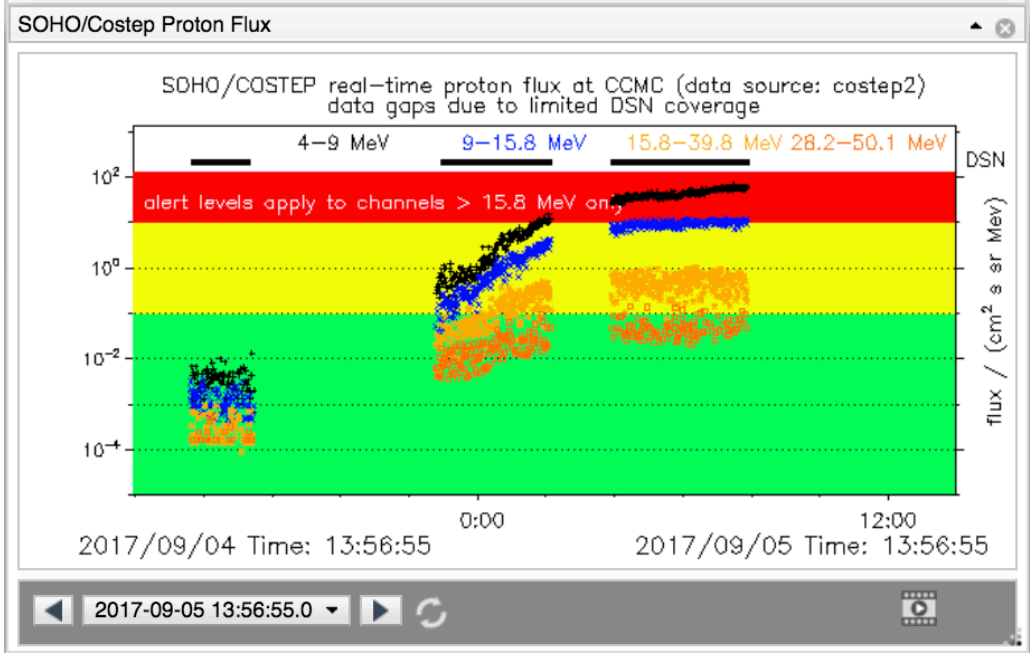
http://go.nasa.gov/2czfgmw

## REleASE Model

Uses detection of high energy *electrons* to predict arrival of high energy *protons*

Input data: SOHO COSTEP electron flux



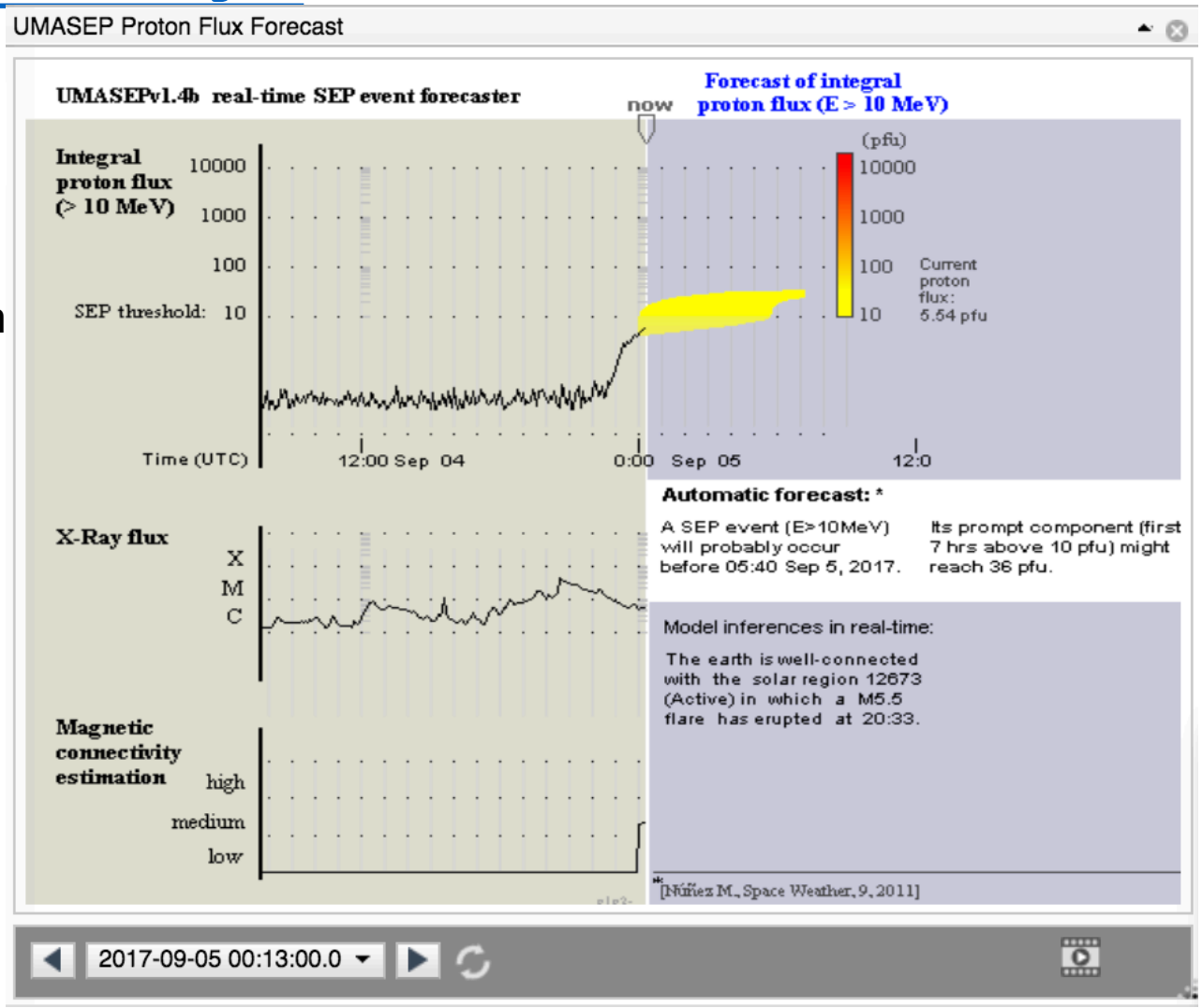
# SEP Prediction at CCMC

http://go.nasa.gov/2czfgmw

## UMASEP Model

Uses magnetic connectivity, current proton flux level to predict the peak flux

Input data: GOES X-ray flux, proton flux



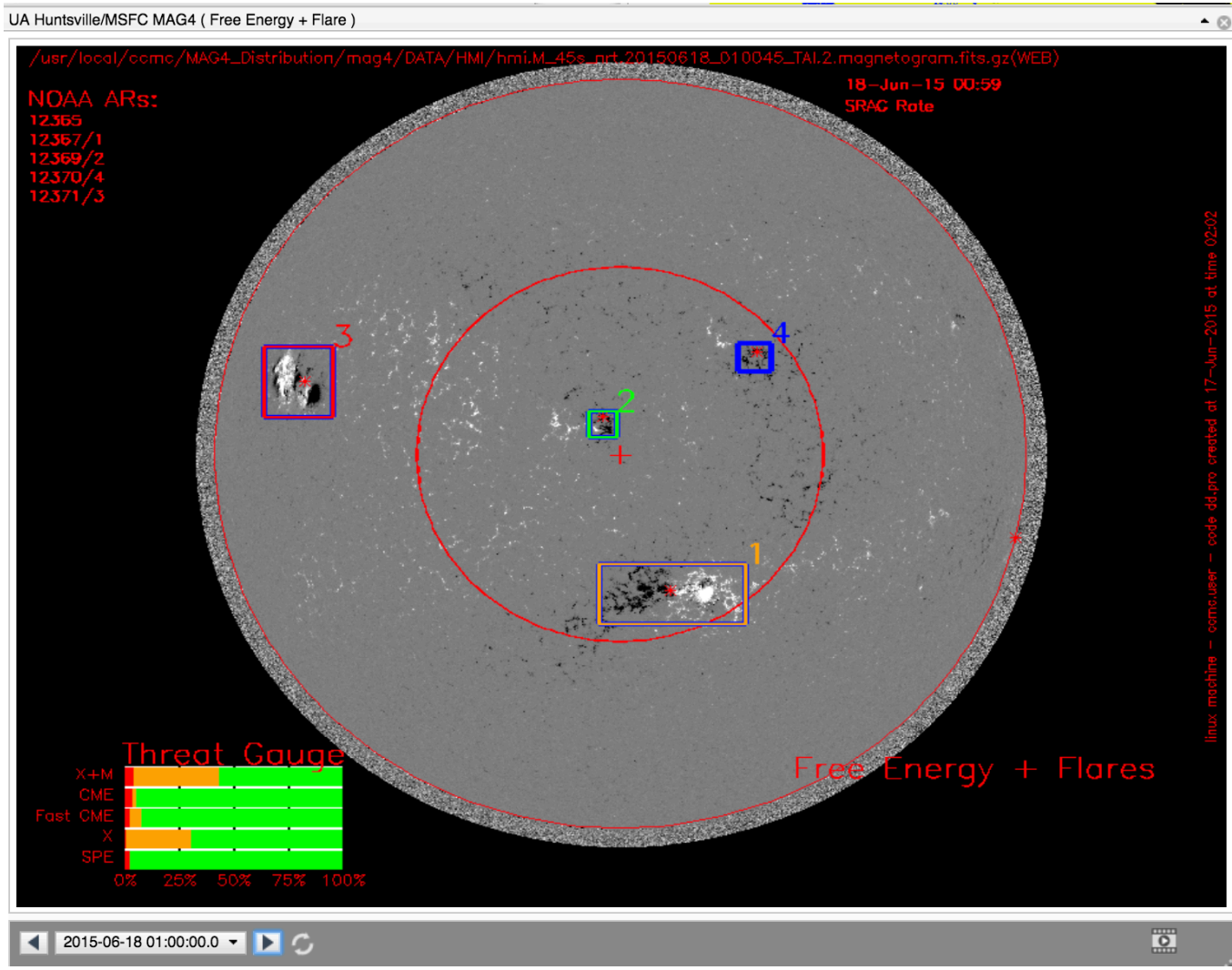
# SEP Prediction at CCMC

http://go.nasa.gov/2czfgmw

## MAG4 Model

Uses active region properties and previous SEP events to produce a probabilistic forecast

Input data: SDO HMI magnetogram



# SEP Context at CCMC http://go.nasa.gov/2czfgmw